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13. ABSTRACT *(Maximum 200 words)*

Observations of boundary-layer flow over heterogeneous surfaces collected from five recent field programs are analyzed. The spatial variation of turbulent fluxes responding to surface heterogeneity are documented for a variety of situations and provides the first study of such variations with adequately sampled surface fluxes. The data analysis also provides the first detailed examination of local circulations and mesoscale fluxes driven by spatial variations of soil moisture and transpiration. The results of these studies are being used to validate models by groups at Colorado State University, Iowa State University and Rutgers. Based on the above observational analyses, the usual bulk aerodynamic formula is modified to include the effect of generation of turbulent fluxes by, unresolved, subgrid mesoscale fluxes. In addition, the transfer coefficients for the grid-averaged fluxes are shown to be generally independent of grid size, except for cases of weak large scale flow over strong surface heterogeneity.

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Coherent Structures, Fluxes and Sampling Problems Over Heterogeneous Surfaces

Final Report

DAAH04-93-G-0019

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Prepared for:
Engineering and Environmental Sciences Division
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STATEMENT OF THE PROBLEM

Most land areas are characterized by complex spatial variability of surface conditions while most practical formulations of turbulence fluxes necessarily apply to homogeneous surfaces. Surface variability complicates the relationship between spatially averaged fluxes and spatially averaged vertical gradients. Such spatial averaging is implied in numerical models of atmospheric flow. While it is unlikely that an accurate practical formulation of fluxes over inhomogeneous surfaces can be constructed, it may be possible to improve upon existing formulations based on homogeneous flow. However, it is necessary to first gain additional experience on the behavior of fluxes over typical inhomogeneous surfaces.

SUMMARY OF RESULTS

The results can be divided into two phases. Phase I is the analysis of surface fluxes over heterogeneous surfaces collected from five recent field programs (Mahrt et al., 1994 a,b; Sun and Mahrt, 1995) . Phase II is modifying the way in which area averaged fluxes are modelled (Mahrt and Sun, 1995, 1996; Sun and Mahrt, 1994). An interpretative literature survey of the various methods to formulate fluxes over heterogeneous surfaces is presented in Mahrt (1996). In addition, new techniques were developed to analyze the turbulence data (Howell and Mahrt, 1994).

"Observations of fluxes over heterogeneous surfaces" (*Boundary-Layer Meteor.*) analyzed data collected from repeated aircraft runs 30 m over alternating regions of irrigated and dry nonirrigated surfaces, each region on the order of 10 km across, during the California Ozone Deposition Experiment (CODE). The variables and their fluxes were decomposed into means for sublegs defined in terms of irrigated and nonirrigated regions and deviations from such subleg means. Since the repeated runs were flown over the same track, compositing the eight flight legs for each of the two days allows partial isolation of the influences of surface heterogeneity and transient mesoscale motions. The momentum and ozone fluxes are more influenced by transient mesoscale motions while fluxes of heat, moisture, carbon dioxide are more influenced by the surface heterogeneity. The momentum field is also influenced by a quasi-stationary mesoscale front and larger scale velocity gradients. The mesoscale modulation of the turbulent flux is numerically more important than the direct mesoscale flux. This spatial modulation of the turbulent fluxes leads to extra Reynolds terms which act to reduce the area averaged turbulent momentum flux and enhance the area averaged turbulent heat flux.

An expanded data set was used to more explicitly study mesoscale circulations

generated by the surface heterogeneity reported in "Observations of fluxes and inland breezes over a heterogeneous surface" (*Journal of Atmospheric Sciences).* An irrigated area, about 12 km across, generates a relatively cool moist inland breeze. As this air flows out over the warmer dryer surrounding land surface, an internal boundary layer develops within the inland breeze which then terminates at a well defined inland breeze front located about 1 1/2 km downstream from the change of surface conditions. This front is defined by horizontal convergence, rising motion, and sharp spatial change of moisture, carbon dioxide and ozone. In the inland breeze downstream from the surface wetness discontinuity, strong horizontal advection of moisture is associated with a rapid increase of the turbulent moisture flux with height. Large moisture flux appears to be partly due to mixing between the thin moist inland breeze and overlying dryer air. As a consequence of the strong vertical divergence of the flux in the transition regions, the fluxes measured even as low as a few tens of meters are not representative of the surface fluxes. The spatial variability of the fluxes is also interpreted within the footprint format.

"Spatial distribution of surface fluxes estimated from remotely sensed variables" published in *The Journal of Applied Meteorology* relates surface fluxes to remotely sensed variables over well defined variations of surface wetness and vegetation. The surface fluxes were estimated from Twin Otter aircraft data collected at 33 m above the surface after correcting for advection and local storage between the aircraft level and the surface. We performed an extensive analysis of flux errors due to finite sample size over heterogeneous terrain. Finally, the heat flux in the surface energy budget was corrected to include fluctuations of heat capacity which becomes important over the irrigated areas. The resulting surface energy budget seems to balance only if mesoscale fluxes are included. The spatial variation of the surface fluxes and atmospheric temperature and moisture are well predicted by a model based on the NDVI, and brightness temperatures of channels 4 and 5 from the NOAA -11 AVHRR. The generality of this relationship is not known.

In "Determination of surface fluxes from the surface radiative temperature" (*Journal of Atmospheric Sciences),* the bulk aerodynamic formulas for heat and moisture using the surface radiative temperature have been evaluated using aircraft and tower measurements in order to study the behavior of the corresponding exchange coefficients, here referred to as the radiometric exchange coefficients. This analysis has been used to evaluate the common practice of predicting the surface heat flux from Monin-Obukhov similarity theory and the surface radiative temperature or temperature from the surface energy budget. The traditional stability dependence for Monin-Obukhov similarity theory does not apply when the surface radiative temperature is used instead of aerodynamic temperature at roughness height. The large difference between the surface radiative temperature and air temperature for unstable conditions requires that the radiometric exchange coefficient is significantly smaller than the one predicted from traditional similarity theory.

The traditional stability function for Monin-Obukhov similarity theory cannot be adjusted to accommodate use of the surface radiative temperature. "Tuning" the roughness

height for heat so that existing Monin-Obukhov similarity theory correctly predicts the surface fluxes leads to unphysically small values for unstable conditions because of the large temperature difference between surface radiative temperature and air temperature. Furthermore, this radiometric roughness height depends on the flow and is poorly related to the roughness height for momentum. In this sense, the roughness height for heat is a poorly defined parameter for the common use with the surface radiation temperature. Analogous problems result with the prediction of the moisture flux based on the saturation vapor pressure computed from the surface radiation temperature.

An adaptive multiresolution filter was developed to decompose time series into fine scale structure (near-isotropic), transporting eddies and large eddies and mesoscale motions such as those driven by surface heterogeneity. The adaptive filter is shown to be physically more precise than conventional filtering and Fourier decomposition. With the latter, the sharp changes associated with the wind gusts are inadvertently included in the fine scale structure even though the gusts are anisotropic and lead to significant transport. These results are published in "An Adaptive Filter: Application to Turbulence" (*Wavelets in Geophysics)* and An adaptive multiresolution data filter: Applications to turbulence and climatic time series (*J. of Atmospheric Sciences).*

The exchange coefficients for area-averaged surface fluxes can become anomalously large when the large scale flow is weak and significant fluxes of heat and moisture are driven by mesoscale motions within the averaging or subgrid area. To prevent this erratic behavior of the exchange coefficient, the "subgrid velocity scale" is introduced to account for generation of turbulence and turbulent fluxes by subgrid mesoscale motions. This velocity scale is motivated by spatially averaging the local velocity used in the bulk aerodynamic relationship. The subgrid velocity scale is distinct from the free convection velocity scale included in the bulk aerodynamic relationship to represent transport induced by convectively driven boundary layer scale eddies. The behavior of the subgrid velocity scale is explored using data from five different field programs. Ubiquitous "nameless" mesoscale motions of unknown origin are found in all of the data sets. The addition of the subgrid velocity scale reduces the dependence of the exchange coefficients on grid size. Based on the data analysis, the subgrid velocity scale increases with grid size and contains a contribution due to surface heterogeneity. This work is published in "Multiple velocity scales in the bulk aerodynamic relationship for spatially averaged fluxes" (*Monthly Weather Review).*

In an invited survey paper for *Boundary-Layer Meteorology* entitled "The bulk aerodynamic formulation over heterogeneous surfaces", I was able to try and tie together the various different approaches applied to boundary layers over heterogeneous surfaces. This interpretative literature survey examines problems with application of the bulk aerodynamic method to spatially averaged fluxes over heterogeneous surfaces. This task is approached by tying together concepts from a diverse range of recent studies on subgrid parameterization, the roughness sublayer, the roll of large "inactive" boundary-layer eddies, internal boundary-layer growth, the equilibrium sublayer, footprint theory and the blending height. Although these concepts are not completely compatible, qualitative scaling arguments based on these concepts

lead to a tentative unified picture of the qualitative influence of surface heterogeneity for a wide spectrum of spatial scales.

Generalization of the velocity scale is considered to account for nonvanishing heat and moisture fluxes in the limit of vanishing time-averaged wind speed and to account for the influence of subgrid mesoscale motions on the grid averaged turbulent flux. The bulk aerodynamic relationship for the heat flux usually employs the surface radiation temperature or, equivalently, the temperature from the modelled surface energy budget. The corresponding thermal roughness length is quite variable and its dependence on available parameters is predictable only in special cases.

An effective transfer coefficient to relate the spatially averaged surface fluxes to spatially averaged air-ground differences of temperature and other scalars can be most clearly defined when the blending height occurs below the reference level (observational level or first model level). This condition is satisfied only for surface heterogeneity occurring over horizontal scales up to a few times the boundary-layer depth, depending on the stability and height of the reference level. For surface heterogeneity on larger scales (small mesoscale), an effective transfer coefficient for the spatially averaged flow must be defined, for which predictive schemes are unavailable. For surface variations on large mesoscales, homogeneous subareas may be maintained where traditional similarity theory is locally applicable. Surface variations on these scales may generate thermally-driven mesoscale motions.

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